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Principal Aspects regarding to the Emergency Evacuation of Large-scale Crowds: A Brief Review of Literatures until 2010

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Abstract

As a kind of emergency evacuation, the large-scale evacuation is an effective measure to mitigate disaster in a sudden crises. Research into the emergency evacuation of crowds has been the focus of many scholars at home and abroad for some time. In this paper, four principal aspects of current research into large-scale crowd evacuation, namely evacuation theories, evacuation modeling, evacuation decision-making and evacuation risk evaluation have been summarized. Of these, evacuation modeling has attracted the greatest interest. While some evacuation models have proved effective tools in evacuation decision-making and risk evaluation, existing evacuation models have not fully considered the uncertain factors in the process of large-scale evacuation.

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Keywords: large-scale evacuation, evacuation analytical tools, contributions and limitations

1. Introduction

When natural disasters such as earthquakes, tsunamis and hurricanes are imminent or have recently occurred, often a large number of people in the affected regions require evacuation. When man-made disasters occur, such as terrorist attacks in a metro station or riots in a major demonstration, emergency evacuation of the large crowd present is usually also required. Industrial accidents, such as hazardous material leakage and explosions, also tend to cause a large number of surrounding residents to be evacuated. Such emergency evacuations, which involve a large number of people and differ from the escape actions of small or medium-sized crowds in ordinary building evacuations, are described as large-scale evacuations. As a kind of emergency evacuation, the large-scale evacuation is an effective measure to mitigate disaster in a sudden crises. It is very important to protect lives and enhance the efficiency of emergency evacuation under crisis situations via emergency evacuation analytical tools which can provide objective information to assist in emergency decision-making.

Research into the emergency evacuation of crowds has been the focus of many scholars at home and abroad for some time. This paper will try to comprehensively review the existing representative work on the emergency evacuation, and more specifically, on the large-scale evacuation. Generally, research on emergency evacuation comprises four principal aspects, namely the crowd evacuation theory, the crowd evacuation modeling, evacuation decision-making and evacuation risk evaluation, as shown in Table 1.

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Table 1.Four principal aspects of the research on emergency evacuation of large-scale crowds

Research aspects	Main contents	Some typical work
Evacuation theory	Correlations of evacuation parameters	Fruin et al.[1,2]; Daamen et al.[3]; Pauls et al.[4];
	Laws of human evacuation behavior	Helbing et al.[5]; Ma [6];
Evacuation modeling	Mathematical models	Okazaki et al.[12]; Helbing et al.[13]; Cruz et al.[14]; Lu et al.[17]; Hughes [20,21]
	Simulation models	Kisko et al.[23]; Sheffi et al.[24]; Hobeika et al.[25]; Tufekci et al.[27]; Owen et al.[28]; Lo et al.[30,31]; Thompson et al.[33,34]
Evacuation decision-making	Evacuation route selection	Cova et al.[35]; Tuydes et al.[36]
	Evacuation population assignment	Gao et al.[37]; Ye [38]
	Evacuation resource allocation	Fiedrich et al.[39]
Evacuation risk evaluation	Gathering risk	Fraser [40,41]
	Traffic risk	Church et al.[42]; Qiang et al. [43]

2. Crowd evacuation theories

Research into evacuation theories dates back to the 1970s and 1980s, and is still one of the important research areas in the field of crowd evacuation. Such research is primarily concerned with studies of the correlations of various parameters in the evacuation process and the laws of human evacuation behavior.

Studies of the various parameters associated with the movement of people during evacuation generally include consideration of the building environment. The methods employed are principally observation and testing, either by observing the movement of populations in real emergencies, or by designing specific simulation scenarios to observe the evacuation behavior of the crowd, in order to ascertain the impact of various evacuation parameters on the crowd movement, such as the work of Fruin et al.[1,2], Daamen et al.[3], Pauls et al.[4] and so on.

For the laws of human evacuation behavior, there are already some promising directions in research into this aspects. One is the discovery and interpretation of a variety of self-organized phenomena in crowd movement [5,6], which contains four categories of typical phenomena, namely the vaulted distribution phenomenon of pedestrians at bottlenecks, the layering phenomenon in opposite pedestrian flows, the zonation phenomenon in cross pedestrian flows and the shockwave phenomenon in high-density populations; another is the analysis and investigation of non-adaptive behaviors in mass evacuation. Casualties in many unexpected events are closely related to the non-adaptive behaviors of the crowds, such as the trampling at the Beijing Miyun Lantern Festival in 2008. Studies of non-adaptive behavior of crowds in emergencies may be divided into two categories. The first is grounded in behavioral psychology, tending to purely qualitative psychological research, and has formed three theories of non-adaptive psychological behavior, namely the panic theory, the decision-making theory [7] and the urgency level theory [8]. The second category focuses on group behavioral modeling and empirically studies the psychological behavioral laws of crowds under emergencies by means of questionnaires, tests and computer simulations.

Although existing evacuation theories have provided a variety of insights into evacuation behavior and psychological reactions in emergency situations, there is still a lack of a comprehensive and coherent theory of non-adaptive crowd behavior. Existing theories have not fully considered all factors, and there are some inconsistencies among different theories. For example, the panic theory and the decision-making theory are founded on opposite assumptions as to whether people are capable of acting rationally under emergencies. Proulx[9] states that the principal difficulties in developing comprehensive theories about human behaviors under emergencies are the lack of real data and the complex characteristics of human behavior. Nevertheless, with the rapid development of data acquisition and computer technology, an increasing number of scholars are focusing on empirical research into the laws of crowd behavior under emergencies, to supplement and deepen existing theories[10,11].

3. Crowd evacuation modeling

Crowd evacuation models have commonly been applied to two categories of application: evacuations from buildings, such as residential buildings and shopping malls, and regional evacuations of the population in an area threatened with disaster, usually centered around an affected building or site (such as a chemical plant where a leak occurs). Although these two categories of evacuation problems have different scales, they are both essentially crowd movement problems. Thus, a variety of research methods and modeling techniques have their own adaptability in these two types of evacuation problems. This article mainly focuses on the second type of evacuation issues: therefore, our review of evacuation modeling research will also focus on these issues.Current research into evacuation modeling may be divided into two major areas: mathematical models and simulation models.

3.1. Mathematical models

The main objectives of studies using mathematical models are to quantitatively describe the laws of mass evacuation under emergency situations; to accurately predict crowd movement; to assess and improve evacuation measures (such as fire fighting facility design), and thereby to lay the theoretical foundations for evacuation simulation models. To date, many mathematical models have sought to analyze the dynamic characteristics of mass evacuation in different research areas. Typical mathematical models include the magnetic model[12], social force model[13], queuing model, optimization model and continuous crowd flow model. For large scale crowd evacuation, considering the complexity of model construction and computation, usually the latter three kinds of mathematical models are more widely accepted.

I. The queuing model

As a classical mathematical theory, queuing theory has been widely applied in the field of crowd evacuation, especially in evacuation scenarios in rail transit stations and so on, where there are better opportunities to analyze the queuing movement characteristic of such crowds.

Queuing theory relies on the assumption that in the process of forming a crowd, pedestrians reach the service desk according to some probability distribution, then receive service and leave according to some queuing rules. The queuing model developed from this idea is known as the M/G/C/C model, and has been widely applied[14]. The advantages of the queuing model are that it can quantitatively describe the dynamic process of crowd formation, simulate congestion, bottlenecks and other phenomena in the queuing system with good visual effect, and rapidly calculate evacuation time. However, human complexity and intelligence is oversimplified, and the model can only describe the crowd formation process under normal conditions.

II. The optimization model

In the optimization model, the evacuation crowd is taken as a whole, composed of pedestrian flow or vehicular flow, while the individual behavioral characteristics of the individual are ignored. This model primarily focuses on the optimization of evacuation planning using network flow methods. Network flow based optimization models have been widely studied in the field of crowd evacuation, especially as regards regional large-scale evacuation. In large-scale evacuation, the key contribution of optimization models is in evacuation route planning[15]. Using a range of optimization methods for different route planning objectives, many studies into evacuation optimization modeling have been conducted

An important step in establishing an optimization model is the realization of the model algorithm. Usually, the route planning problem is abstracted into a kind of discrete network flow problem with time. One feasible way to solve this problem is to transform the dynamic network into an extension of the static network, which then can be solved by classic polynomial time algorithms[16]. However, this method requires a huge amount of storage space for the time extension graph, and may therefore be unsuitable for large-scale evacuations. Another algorithm which facilitates use of optimization models in large-scale evacuation is the "heuristic" algorithm. The heuristic algorithm does not pursue the optimal solution of the optimization equations, but by employing suboptimal solutions, it can effectively reduce the amount of computation and storage requirements. Typical tools for solving evacuation planning optimization problems are the SRCCP、MRCCP and CCRP heuristic algorithms proposed by Lu et al.[17], and the improvements to the CCRP algorithm proposed by Kim et al.[18].

III. The continuous crowd flow model

A macro model of crowd evacuation, the fluid dynamics crowd flow model was first proposed by Henderson[19]. In this model, crowd movement behaviour is analogous to the flow of gas or fluid, and by taking the crowd as a continuous flow of medium, kinetic equations describing the evacuation process of the entire crowd may be established. The characteristics of crowd movement, such as crowd density and local speed, are described without consideration of individual differences in the crowd: only the objectives of the crowd movement and the interactions between people are important. Adapting Henderson's crowd flow model, Hughes[20,21] applied the continuum theory of traffic flow to study crowd behaviors, and proposed the continuous crowd flow theory by deducing the equations of crowd motion using mathematical knowledge. This continuous crowd flow theory has become the foundation of continuing research into congestion and the stampede mechanism in large-scale crowds under emergencies [22].

3.2. Simulation models

The large-scale evacuation problem, like small and medium-sized crowd evacuation problems, is essentially a personnel movement problem. Therefore, the goal of evacuation simulation models is to simulate the movement of personnel using computer simulation tools developed from mathematical models. The movement of personnel may be the movement of either a single individual or the entire crowd. Therefore, according to the focus of each simulation, i.e. on the crowd as a whole or on the individual, simulation models may be categorize as macro and micro models.

Macro simulation models consider the evacuation crowd as a whole and ignore the behavioral characteristics of the individual, focusing on the optimization of evacuation planning strategies (such as obtaining the largest capacity from evacuation channels and avoiding bottlenecks along evacuation routes). Unlike macro models, micro models are concerned with the motion characteristics of the individuals in the crowd, and study the evacuation process of the whole crowd by establishing individual movement rules. Typical representative models are shown in Table 2

Table 2. Typical simulation models

Typical macro simulation models	Typical Micro simulation models
EVACNET[23];NETVAC[24];MASSVAC[25]; DYNEV[26];OREMS[27]	BuildingEXODUS[28];EXITT[29];SGEM[30,31]; CAFE[32];SIMULEX[33,34]

4. Crowd decision-making during evacuations

Problems considered in evacuation decision-making include the decision whether to evacuate, and how to ensure safe evacuation of the population through effective coordination of a range of resources. Emergency decision-making in evacuations may be divided into three aspects: pre-evacuation decision-making, which is primarily concerned with the question of whether large-scale evacuation is required; decision-making during evacuation, which is comprised of a variety of decisions related to the transfer of the affected population from dangerous to safe destinations; and decision-making after evacuation, where the principal concern is regulation of the social and psychological responses of the population who have suffered a disaster and undergone large-scale evacuation. Below, we review studies of decision-making during evacuation, which focus on three issues, namely evacuation route selection, evacuation population assignment and resource allocation.

4.1. Evacuation route selection

Evacuation route selection usually refers to the selection of optimal evacuation routes: thus, optimization models have been widely applied in this field. Usually, there are three kinds of optimal evacuation routes: the routes with the shortest spatial distance, the routes with the shortest evacuation time, and the routes through which the largest number of people can be evacuated. Most of the existing studies of evacuation route selection have used the shortest evacuation time as the most important optimization objective, and analyzed the selection of evacuation routes using mathematical models or simulations. For example, Cova et al.[35] proposed a lane-based large-scale evacuation network flow model and applied this model to the selection of optimal evacuation routes in a complex road network. Tuydes et al.[36] proposed and developed a lane reversal (contraflow) model in traffic emergency evacuation route selection.

However, most of these studies rely on the hypothesis that the travelling speed at every arc (or road section) in the evacuation network is constant, or constant at different times. Little research has considered the real-time impact of a sudden disaster on the route travelling capability of the evacuation network. It has been demonstrated that in many disasters, such as fires and poison gas leakage and diffusion, the spread of smoke, gas or radiation develops dynamically with time, thus the route travelling capability under the influence of these disasters will also vary with time. Therefore, it is very important to analyze the dynamic influence of disasters on evacuation network parameters, and modify the route selection optimization strategies accordingly, using mathematical or simulation models.

4.2. Evacuation population assignment and resource allocation

Evacuation population assignment determines the number of people who should be assigned to each evacuation route to ensure as many members as possible of an affected population are evacuated in a limited time and to limit the number of people at each refuge to its maximum capacity. This problem is in fact a traffic assignment problem, more specifically an

Origin-Destination (OD) problem [37]. Traditional traffic assignment problems include four stages, namely traffic generation, traffic distribution, mode partition and route assignment. According to differences in optimization function, traffic assignment models may be categorized as system optimal models and user optimal models, and both kinds of traffic assignment models may be applied to evacuation population assignment. For example, using the system optimal model as a reference, and assuming multiple origins and multiple evacuation routes, Ye[38] studied the allocation of evacuees along each alternative route.

To a large extent, generous resource allocation can ensure the smooth evacuation of large-scale crowds under emergencies. The rational allocation and efficient use of limited emergency resources (rescue staff, evacuation vehicles, etc.) to achieve the maximum benefit from those resources is an important aspect of the study of large-scale evacuation decision-making. To date, considerable research has been conducted into evacuation resource allocation, and especially to the topic of resource scheduling. For example, Fiedrich et al.[39] proposed a resource allocation and transportation optimization model for multiple affected areas after an earthquake, enabling the injured to be evacuated to hospitals and other safe places as soon as possible.

However, it should be noted that evacuation population assignments conducted using traffic assignment methods have ignored the subjective initiative of evacuees, as well as the question of whether evacuees can follow the established rational evacuation route. Hence, population assignment to evacuation routes has been too optimistic. Therefore, when we analyze the factors that can affect evacuation at crowd level, the randomness of crowd route selection behavior should be examined, and the subjective initiative of the crowd during route optimization should also be considered.

5. Crowd evacuation risk evaluation

To date, research into large-scale mass evacuation risk has primarily been concerned with two aspects, i.e. gathering risk and the traffic risk of the evacuation crowd.

When a large-scale, high density crowd gathers, and the surrounding environment is dangerous, some events such as stampeding and trampling may easily occur and result in casualties, bringing high risk to mass evacuation. Research into crowd gathering risk primarily focuses on crowd moving behaviors and crowd psychological characteristics to determine the frequency of occurrence of injuries in a crowd, and to investigate the deep-seated mechanisms of the occurrence, development and evolution of accidents. CRISP, proposed by Fraser[40], is a risk assessment model extended from simulation methods. It can establish the random distribution of evacuation time through repeated simulation, integrating probability factors into the simulation model, and incorporating statistical analysis methods into the evaluation of evacuation risk. This model has been widely used in the assessment of fire evacuation risk[41].

With respect to the traffic risk of large-scale evacuating crowds, most existing research considers the impact of various risk factors on evacuation results, with the aid of evacuation models. A typical example is the critical cluster model (CCM) proposed by Cova et al.[42]. This model analyzes the evacuation risk of each area by integrating the amount of affected population with the road capacity. An amended model was further proposed[43], to enable the evacuation traffic risk assessment model to approximate actual situations more accurately.

6. Concluding remarks

In this paper, we have summarized four aspects of current research into large-scale crowd evacuation, namely evacuation theories, evacuation modeling, evacuation decision-making and evacuation risk evaluation. Of these, evacuation modeling has attracted the greatest interest. While some evacuation models have proved effective tools in evacuation decision-making and risk evaluation, existing evacuation models have not fully considered the uncertain factors in the process of large-scale evacuation. Moreover, it is difficult for a single model to comprehensively analyze the various factors that can influence evacuation. In our future studies, it is important to consider the impact patterns of disaster factors, crowd factors and rescue factors on large-scale evacuation under various emergencies. We suggest that it may be feasible to use some existing models and algorithms (such as the optimization model, CCRP algorithm and continuous crowd flow model) to analyze relevant factors, to use some evacuation theories (such as non-adaptive behavioral theory) to study the influence of relevant factors on the psychology and physiology of the evacuating crowd, and the indirect effect on the evacuation process. Such work will not only supplement and deepen existing evacuation theories and models, but also provide more theoretical and technical support in evacuation decision-making by considering various uncertain aspects and risks.

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